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MATERIALS PROCESSING

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IMPROVED DETERMINATION OF NONDESTRUCTIVE REGIMES FOR LASER PROCESSING OF GLASS AND CERAMIC PLATES

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Unilateral heating of a glass or ceramic plate, lightly secured along the edges, by a surface source is examined within the framework of a quasistatic uncoupled problem of thermoelasticity. The analytical relation, which is a criterion for the thermal strength of a plate, is improved for the case where the elastic modulus and the linear thermal expansion coefficient of the plate material are linear functions of temperature.

Key words: laser processing, plate, nondestructive regimes, thermal strength criterion, quasistatic problem of thermoelasticity.

Together with the conventional high-temperature annealing, optical glass and ceramics are also processed machined by irradiating their surface with continuous-wave CO_2 laser radiation [1 – 4]. Fast unilateral heating followed by slow cooling of the surface of a plate induces relaxation of the stresses which appearing due to polishing. Processing regimes where the thermoelastic stresses are determining in a technological process can arise in a plate as a result of unilateral heating. In [1], to determine the nondestructive processing regimes the solution of an uncoupled quasistatic problem of thermoelasticity was studied for a plate lightly secured along its edges and an analytic solution which is a criterion for the thermal strength of a plate heated by a surface source was obtained:

$$\frac{\sigma_t (1-\nu)}{E\alpha_T (T_f - T_0)} \geq \frac{\frac{1}{6} + \frac{2}{\pi^2}\sum_{n=1}^{\infty}\frac{(-1)^n}{n^2} e^{-n^2\pi^2\tau}}{\tau + \frac{1}{3} - \frac{2}{\pi^2}\sum_{n=1}^{\infty} n^{-2} e^{-n^2\pi^2\tau}}, \qquad (1)$$

where σ_t is the ultimate tensile strength of the plate material; ν is Poisson's ratio; E is the elastic modulus; α_T is the linear thermal expansion coefficient of the plate material; T_f is the softening temperature of the plate material; T_0 is the initial temperature; $\tau = at/h^2$ is the Fourier number; a is the thermal diffusivity of the plate material; t is the laser irradiation time; and, h is the plate thickness.

Equation (1) is derived under the following assumptions:

– the flux density is uniformly distributed over the cross section of the laser beam and is constant in time;

– the absorption coefficient of the plate material is quite high and the absorption of laser radiation in optical and quartz glasses can be regarded as surface absorption (this condition holds well for continuous-wave CO_2 laser radiation, whose penetration depth is ≈20 μm [4] for these materials);

– there are no radiation losses on the irradiated surface;

– the properties of the plate material are independent of the temperature arising under the action of the laser.

As a rule, the elastic modulus and the linear thermal expansion coefficient of the plate material can be regarded as linear functions of temperature:

$$E = E_0 - E_1 (T - T_0);$$
$$\alpha_T = \alpha_0 + \alpha_1 (T - T_0), \qquad (2)$$

where E_0 is the value of the elastic modulus at the initial temperature T_0; α_0 is the linear thermal expansion coefficient at the initial temperature T_0; T is the running value of the temperature; and, E_1 and α_1 are coefficients.

The thermoelastic stresses produced in a plate, lightly secured along the edges, by a temperature field are given by the following expressions:

$$\sigma_x(\xi, \tau) = \sigma_y(\xi, \tau) = \frac{E\alpha_T qh}{(1-\nu)\lambda}\left\{\frac{12\xi^2 + 12\xi - 1}{24} - \frac{2}{\pi^2}\sum_{n=1}^{\infty}\frac{(-1)^n}{n^2}\cos\left[\frac{\pi n}{2}(2\xi + 1)\right] e^{-n^2\pi^2\tau}\right\}, \qquad (3)$$

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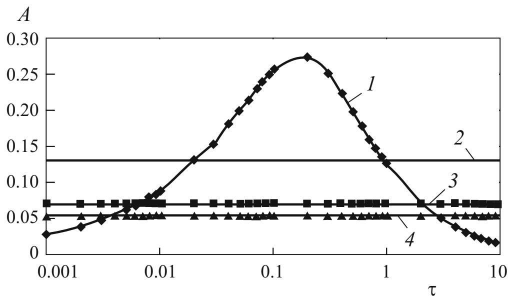

Fig. 1. Graphical solution of the inequality (4): *1*) $f(\tau)$; *2*, *3*, *4*) values of A for $K < 0$, $K = 0$, and $K > 0$, respectively.

where λ is the thermal conductivity of the plate material; q is the flux density of the laser radiation absorbed by the surface of the plate; $q = q_0(1 - R)$; q_0 is the flux density of the laser radiation incident on the surface of the plate; R is the reflection coefficient; $\xi = z/h$ is a dimensionless coordinate; and, z is the coordinate measured from $+h/2$ to $-h/2$.

Analysis of Eq. (3) shows that the thermoelastic stresses vary along the plate thickness from maximum compressive in the plate section $\xi = 1/2$, where the temperature has its maximum value, to the maximum tensile in the plate section $\xi = -1/2$, where the temperature assumes its lowest value. Substituting the expression (2) into Eq. (3) and performing mathematical transformations in the sequence presented in [5] we obtain a more accurate criterion for the thermal strength of the plate:

$$\frac{\sigma_t\,(1-\nu)}{E\alpha_T\,(T_f - T_0)(1+K)} = A \geq f(\tau), \qquad (4)$$

where

$$K = \left(\frac{\alpha_1}{\alpha_0} - \frac{E_1}{E_0}\right)(T_f - T_0); \qquad (5)$$

$$f(\tau) = \frac{\frac{1}{6} + \frac{2}{\pi^2}\sum_{n=1}^{\infty}\frac{(-1)^n}{n^2}e^{-n^2\pi^2\tau}}{\tau + \frac{1}{3} - \frac{2}{\pi^2}\sum_{n=1}^{\infty} n^{-2} e^{-n^2\pi^2\tau}}. \qquad (6)$$

The inequality (4) was obtained neglecting second-order infinitesimals, including the product $\alpha_1 E_1$. The left-hand side of the inequality, just as in [5], is a constant characterizing the ratio of the ultimate tensile strength of the plate material to the maximum tensile stresses in the plate taking account of the linear dependence of the elastic modulus and the linear thermal expansion coefficient (CLTE). The right-hand side of the inequality is a function of a dimensionless parameter — the Fourier number. The function $f(\tau)$ is independent of the properties of the material. This function is shown in Fig. 1 as a convex curve with maximum value 0.275 at $\tau \approx 0.2$.

Our subsequent analysis pertains to K8 optical glass whose CLTE can be represented by the linear function [7] $\alpha_T = 7.2 \times 10^{-6} + 4.6 \times 10^{-9} \times (T - T_0)$. There is no reliable information in the literature or GOST 13659–85 "Colorless optical glass" the elastic modulus of K8 glass. For this reason we shall confine our attention to a qualitative analysis of the inequality (4). Setting α_1 and E_1 to zero in Eq. (4) transforms the inequality (4) into the expression (1). The inequality (1) does not hold for $0.006 < \tau < 2.2$ (see Fig. 1). Therefore, thermoelastic stresses will destroy the plate at a lower flux density than required for the plate surface to reach the softening temperature. If the CLTE of the plate material grows more rapidly with increasing temperature than the elastic modulus decreases, then $K > 0$ and the variation range of the parameter τ where thermoelastic stresses can destroy the plate expands. If $K < 0$, the variation range of the parameter τ where thermoelastic stresses can destroy the plate shrinks. Setting $E_1 = 0$ in Eq. (5), the left-hand side of the inequality (4) assumes the value 0.053 and the inequality no longer holds for $0.004 < \tau < 2.6$. When heated by a surface source, materials for which the left-hand side of the inequality (4) is greater than 0.275 do not break down as a result of thermoelastic stresses. Examples of such materials are quartz glasses [8] and KO6 optical ceramics [5]. For most optical glasses and ceramics, however, a preliminary analysis of the thermal strength must be done using the relation (4) in order to pick nondestructive laser processing regimes.

In summary, the inequality (4) is a criterion for thermal strength of a plate loosely secured along the edges and heated unilaterally by a surface source and makes it possible to determine nondestructive regimes for laser processing of the surfaces of optical and ceramic materials taking account of the temperature dependence of the elastic modulus and the linear thermal expansion coefficient.

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